NARROW-BAND, WIDE-RANGE TUNEABLE THZ SOURCE BASED ON THE SLOTTED-FOIL TECHNIQUE

J. Pfingstner*, E. Adli and H. Holmestad, University of Oslo, Oslo, Norway
S. Bettoni and S. Reiche, PSI, Villigen, Switzerland

Abstract

The FEL user community has expressed a strong interest in a THz source for the excitation of their samples in pump probe experiments. The demanded THz properties are challenging to achieve, as they include a narrow bandwidth of <5-10%, the possibility of frequency tuning between 1 and 20 THz, a THz pulse energy of about 100 μJ, and a fixed phase relation from shot-to-shot. To fulfill these specifications, an accelerator-based source is proposed in this paper. It utilises the slotted-foil technique to create a pre-bunched electron beam that is injected into a helical undulator. Detailed simulation studies presented in this paper show that the corresponding undulator radiation has the demanded properties.

INTRODUCTION

THz radiation is of high interest for material scientists, especially in connection with pump-probe experiments at X-ray free-electron laser facilities. Different processes in materials, e.g. grid oscillations (phonons), oscillation of free electrons (plasmons) and spin coupling (magnons) occur with frequencies in the THz regime. In order to study this processes, the user community of the SwissFEL [1] has concluded that a THz source to pump material samples should have the following properties:

- Tuneable frequency range: 1 THz to 20 THz.
- Bandwidth: <10%.
- Pulse energy: >100 μJ.
- Fixed relation between THz phase and X-ray pulse arrival time.

Radiation sources in the THz regime exist [2], but have either a small bandwidth and a small pulse energy [3], or a high pulse energy but a broadband frequency spectrum [4]. To fulfill the demands posed by the material scientists, an electron beam based design is presented in this paper that utilises the slotted-foil technique [5]. At this technique, the electron beam is pre-bunched at the correct wavelength by sending it through a foil with slots while it is horizontally tilted. The pre-bunched beam is then send to an undulator where the THz radiation is created via the free-electron laser process. The pre-bunching ensures the fixed phase relation from pulse to pulse, which does not occur in SASE FELs.

FACILITY OVERVIEW

The layout of the proposed facility is schematically depicted in Fig. 1. A photo-cathode electron gun creates a 2.5 nC beam with and normalised emittance of about 2 μm in both planes. This beam is accelerator by an S-band accelerating structure to 25 MeV. The injector design is based on the SwissFEL design [6] and has been adapted to create higher beam charges with the help of ASTRA simulations [7]. The acceleration is performed 31 degrees off-crest to create a total correlated energy spread of 7% along the 6 mm long bunch.

The following imprint optics creates disperions η=-0.46 m at the foil location, which results in combination with the correlated energy spread of the beam in the necessary horizontal beam tilt for the imprint. To create a bandwidth <10%, 15 micro-bunches are imprinted by the 15 foil slots. The distance of the micro-bunches is 300 μm which corresponds to 1 THz. The final bunch length is 4.5 mm where the rest of the beam has been cut by the foil to remove tails in the longitudinal phase space due to longitudinal space charge forces. The optics design has been performed with the help of MADX [8] and ELEGANT [9] simulations. The design is challenging due to the large energy spread, large dispersion and the need to avoid longitudinal smearing. With the help of sextupole magnets the chromaticity could be sufficiently corrected up to the foil location where the imprint shown in Fig. 2 was created. The uneven, chirp-like micro-bunch spacing can be improved by adapting the foil slit spacing accordingly. The design of the chromaticity correction downstream of the foil is subject to future work, but unavoidable to ensure a useful beam transport.

After the dispersion is removed by the second part of the imprint optics, the beam is sent through a bunch compressor that allows to tune the spacing of the micro-bunching to create THz radiation from 1 THz to 4 THz. The full frequency tuning is achieved by tuning the undulator also to higher harmonics of the pre-bunching. Before the beam is sent through this undulator, its correlated energy spread is removed with the help of a passive de-chirper unit that was designed with available analytical expressions [10]. The overall length of the facility is about 13 m.

FOIL AND COLLIMATOR DESIGN

The foil scattering process was modelled and simulated in GEANT4 [11] where both, ionisation and Bremsstrahlung decays contribute significantly. The simulation setup is illustrated in Fig. 3. The incoming electrons at the bottom of the plot are loaded from the ELEGANT beam file. They are scattered by the foil grid, collected by a GEANT4 col-

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[*] juergen.pfingstner@fys.uio.no

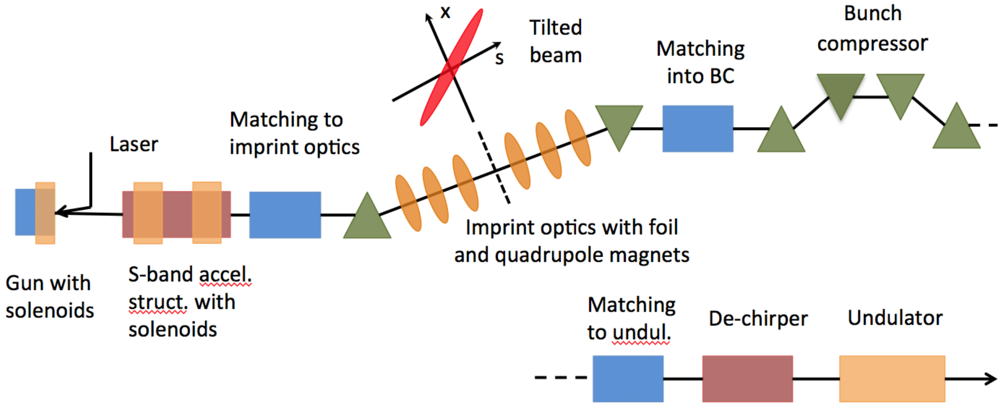

Figure 1: Overall layout of the slotted-foil THz facility.

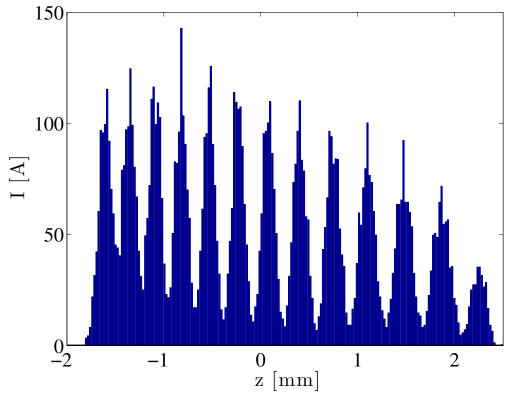

Figure 2: Beam current profile directly after the imprint foil for 13 micro-bunches spaced for a wavelength of 1 THz.

lector element and written to an ELEGANT output file. For illustration only four incoming electrons have been used in this setup. Apart from the loaded electrons also two Bremsstrahlung photons reach the collector.

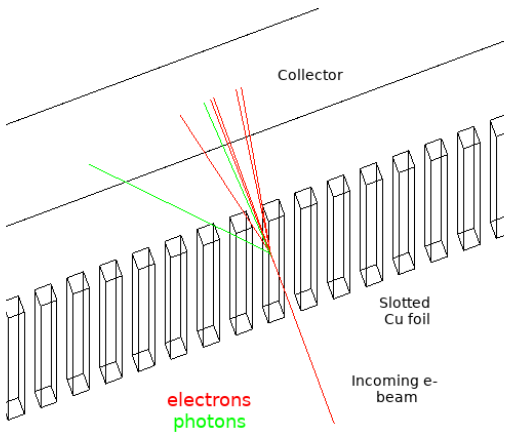

Figure 3: Particle scattering simulation setup with a 1 mm cooper foil.

Different foils have been tested and the results are summarised in Table 1. The listed materials are ordered according to their density, which determines to a large extend the scattering strength. No foil material is able to stop the incoming electrons directly, and the energy deposition is rather small. Instead, the scattered particles have to be removed with the help of a collimator downstream of the foil. Even a beryllium foil of only 0.1 mm width results in an average scattering angle of 53 mrad, which corresponds to an emittance increase of about a factor of 1000. Therefore, it seems very difficult to transport the scattered particles any further and it is necessary to collimate them right after the foil. For beryllium and aluminium the drift space between foil and collimator would be rather long. For tungsten, on the other hand, the scattering is so strong that it would be difficult to collect the scattered particles in a controlled way. Instead, cooper and steel are a very good choice, where cooper is preferable due to its higher heat conductivity. For this case, a two 5 cm long tungsten plates that are located 10 cm downstream of the foil can collimate the beam very efficiently. With a vertical plate separation of 1 cm, 96% of all scattered particles can be collimated. First conservative estimates show also that the heating of the foil and the collimator are not an issue, but a certain activation has to be expected. No additional shielding is expected to be necessary, however.

Table 1: Comparison of Different Foil Material Choices

Foil	ΔE [MeV]	ΔE [%]	σ_{sc} [mrad]
Be, 0.1 mm	0.03	0.10	53
Be, 1 mm	0.26	1.05	173
Al, 1mm	0.42	1.68	175
Cu, 1 mm	1.31	5.24	275
Steel, 1 mm	1.23	4.93	257
W, 1 mm	3.21	12.8	608
W, 2 mm	7.25	29.04	1113
W, 50 mm	24.81	99.23	5696

UNDULATOR SIMULATIONS

The challenge for the undulator section is to create as long wavelength as 300 μm (1 Thz) and at the same time allowing a large tuning range up to 20 THz. To facilitate this, a long undulator period λ_u of 6 cm is used and an undulator parameter K that is varied from 4.9 to 0.75. This corresponds to an on-axis field of 0.88 T to 0.09 T. The design foresees a helical undulator to profit from the strong natural focusing in both planes, where the matched beta function is only 0.1 m at 1 Thz.

The creation of the THz radiation in the undulator has been simulated with the code GENESIS [12] with an artificially generated beam that is fully bunched at 1 THz (15 micro-bunches) and matched to the undulator beta function. An important factor for the THz production is the strong space charge effect, which acts as a de-bunching force and lowers the produced output power. Two longitudinal and one azimuthal space charge monopole modes (Fourier components) had to be included in the simulations with a minimum number of 150000 particles to achieve convergence in the simulation results. The second important imperfection to the FEL process is diffraction. Due the small beam size and the long wavelength, the Rayleigh length is in the same order as the beam size. To account for this effect the simulation step size for the FEL process had to be reduced by a factor of 50 compared to the standard setup.

With this setup, the energy and the bandwidth of the created THz pulse has been determined as a function of the undulator length. The are depicted in Fig. 4 and Fig. 5, respectively. The simulations have been carried out with and without a circular waveguide of 1 cm radius inserted into the undulator. This waveguide guides and collects the created THz radiation, while it otherwise would elude outwards due to the strong diffraction effect. As can be seen, both scenarios allow to produce a THz pulse energies that exceeds the specification of 100 μJ already with a very short undulator length of about 0.25 m. But especially for an undulator length between 0.25 m to 1.5 m the waveguide option produced significantly higher power/energy. Also in terms of bandwidth, the waveguide option seems to be preferable, and it can achieve the demanded specification of <10%.

Without the waveguide, the power production settles after about 0.25 m, since the diffraction effects are attenuating the light amplification. The rise of the power at around 1.5 m is not due to the usual FEL process, but due to edge effects that strongly boost the radiation production. These edge effects have been observed and described earlier and are known as the super-radiative regime [13]. This effect has not been observed for the case with waveguide, which is the reason for the more steady energy curve and the lower bandwidth.

CONCLUSIONS AND FUTURE WORK

A conceptual design of a potential future THz source has been presented. This source would feature radiation properties as a narrow bandwidth <10%, a tuneable frequency between 1 THz to 20 THz, as well as pulse energies of several 100 μJ. This properties can be achieved with a pre-bunched electron beam send through a helical undulator. This paper covers most aspects of this THz facility that will be about 13 m long. The challenge of the design is the transport of the electron beam transport due to its large correlated energy spread and the dispersion. So far the beam could be transported up to the imprint foil in tracking studies, but a further optimisation with respect to energy acceptance, correction of non-linear distortions and longitudinal beam smearing is necessary downstream of the imprint foil. This is subject of future work. Besides the design itself, another interesting outcome of this work is the observation of the strong THz radiation creation due to edge effects, which could be used in the future to significantly simplify the design.

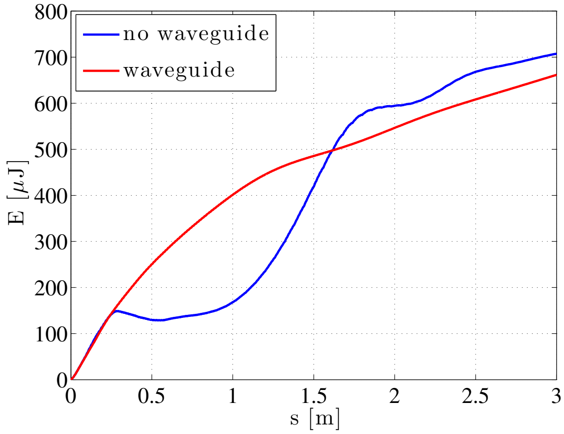

Figure 4: Energy of the THz radiation pulse along the undulator.

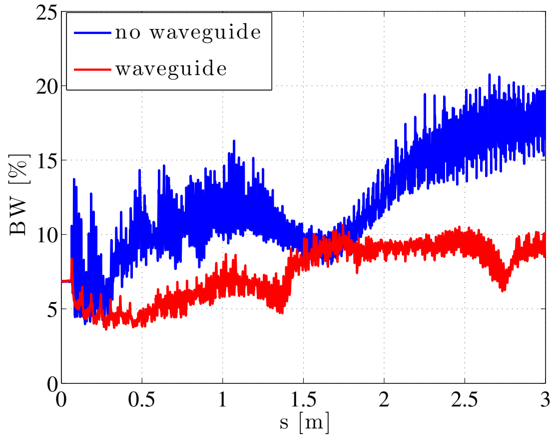

Figure 5: Bandwidth of the THz radiation pulse along the undulator.

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